Lighting the Way to the Stars

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NASA has long recognized the importance of biological life-support systems to remove carbon dioxide, generate oxygen, purify water, and produce food for long-duration space missions. Experiments to understand the effects of the space environment on plant development have been performed since early days of the space program. In the late 1970s, NASA sponsored a series of workshops to identify issues associated with developing a sustainable, biological life-support system for long-duration space missions. Based on findings from these workshops, NASA's Controlled Ecological Life Support Systems (CELSS) program began funding research at university and field centers to systematically conduct the research identified in those workshops. Key issues were the necessity to reduce mass, power/energy requirements, and volume of all components.

During those workshops, it became apparent that lighting was a critical component of such systems, and that significant, if not insurmountable, challenges had to be overcome to incorporate fluorescent or high-intensity discharge (HID) lamps into space-based plant-growth systems. Beyond the operational issues associated with lamp replacement, heat removal, and design, safety was identified as a critical issue that needed to be addressed. The prospect of lamps breaking with small chards of glass and mercury floating around the cabin created a safety nightmare (1)!

At the time, NASA was funding University-based centers to foster the commercial development of plant-growth technology for space. One such center, The Wisconsin Center for Space Automation and Robotics (WCSAR) in Madison Wisconsin, evaluated the growth of a number of different plant species lighted with red-light-emitting diodes, and the first US patent for growing plants under LEDs subsequently was awarded (2).

The payload-development team at Kennedy Space Center worked closely with WCSAR to test and design for the inclusion of LEDs into plant growth chambers for space. A series of hardware tests in space were scheduled to evaluate the technology in the mid-1990s. The first testing of LEDs involved the Astroculture™ Plant Growth Chamber, which flew on Space Shuttle in February 1995, but no plants were grown during that mission. The final technology-demonstration experiment with Astroculture™ involved growing potatoes from cuttings under LEDs on a follow-up mission to the Space Shuttle Mission. Ironically, the ultimate success of the Astroculture™plant test can be traced to the difficulties in actually launching the Space Shuttle mission (STS-73), which had six launch delays before it successfully launched on its 7th try. After the initial delay, the plant chamber was removed from the Space Shuttle and returned to payload-processing laboratories at Kennedy Space Center where it was discovered that temperatures got very high, effectively killing developing meristems on the potato cuttings! A quick bit of troubleshooting revealed the assumption that “LEDs don’t give off heat” is a myth, and that that a more effective system for managing the heat emitted from electrical connections of the diodes had to be developed. The ensuing launch delays provided the time necessary for important changes to be implemented that resulted in the first successful use of LEDs to grow plants in space in October 1995 (3).

Concurrent with development of LEDs for flight hardware, experiments were conducted at the Kennedy Space Center to determine whether narrow-spectrum LEDs could be used to support plant growth for long-duration planetary missions. It was quickly observed that while red LEDs could support photosynthesis, some blue light was necessary for normal morphology of many crops (Figure 1). These tests were very encouraging, revealing that productivity and normal morphogenesis could be achieved using only red and blue wavelengths. However, one issue associated with providing only red/blue wavelengths was that the plants took on a dark-purple, or black appearance, and it was impossible to visually assess the health or 'color' of the leaves (Figure 2). However, the addition of a bit of green light, which was more reflected than absorbed from the outer leaves gave plants back their familiar green color that could be assessed for stress status (Figure 3). In addition to giving the characteristics of 'white' light, green made it much easier to work with the plants in the chambers, especially via remote imaging (4).

Throughout the 1990s, there were a number of rapid advancements in lighting systems for plant chambers, and designs to increase light levels were introduced. These approaches typically included inclusion of very high density, discrete arrays (LED light engines) with red, blue, green and far-red LEDs to generate enough PAR for photosynthesis and appropriate spectra for normal plant morphology. We were aware that UV light would induce the formation of secondary-metabolite compounds, and wondered if the production of nutritionally desirable bioactive compounds could be increased by altering the growth spectrum using LEDs. This led to a number of experiments being conducted to test the effects of timing and composition of red/blue/green/near-infrared wavelengths on growth and composition of lettuce. These results were very encouraging, indicating that both crop yield as well as concentration of bioactive compounds could be increased through management of the spectrum without increasing power use (5).

The small-scale tests were then expanded to larger-scale lights for a Vegetable Production Chamber (VEGGIE) to allow growth of salad crops on the International Space Station (ISS). The VEGGIE LED light cap was designed and built by Orbitec (Madison, Wisconsin) consisting of red, blue, and green wavelengths. The prototypes allowed the relative amounts of red/blue/green wavelengths to be controlled separately, thereby providing capability to independently optimize lighting conditions for each stage of plant development (Figure 4). However, the capability, while valuable, had to be dropped in order to simplify operation of VEGGIE during initial testing on ISS. Thus, the fixed spectrum has been optimized to maximize production of biomass and bioactive compounds, while minimizing power usage and mass. The design also allows the light cap to be positioned very close to the crop canopy, without overheating or damaging plants. VEGGIE was launched to ISS for an operational test in 2014, and a crop of lettuce was grown, harvested, and returned to Earth for analysis (Figure 5).

The inclusion of LEDs for bioregenerative life-support systems on planetary surfaces poses similar but unique challenges for integrating plants into crew living quarters. In 2010, NASA included a plant-growth system as part of a large-scale operational test in the Arizona desert to evaluate technology being developed for exploring the moon. The Habitat Demonstration Unit (HDU) contained laboratories for biology, geology, and medicine on the lower level, and living and sleeping area the upper level. A plant 'Atrium' was established between the laboratory and living quarters of the HDU on the ISS (Figure 6) to grow fresh salad crops for the crew. It's LED array consisted initially of red and blue LEDs, which were intended for the plants, but produced an eerie purple glow over the lab when fluorescent lamps were turned off. Based on crew input that it was difficult to work in that light, white LEDs were installed and tested the following year (6).

The advances in development of ‘white’ LEDs (blue LEDs + a phosphor), and the availability of different spectra that can be delivered by the technology has resulted in increased testing of white LEDs for long-duration space applications. So, it may be that after a quarter century of testing and development we are rediscovering the value of white light!

Citations

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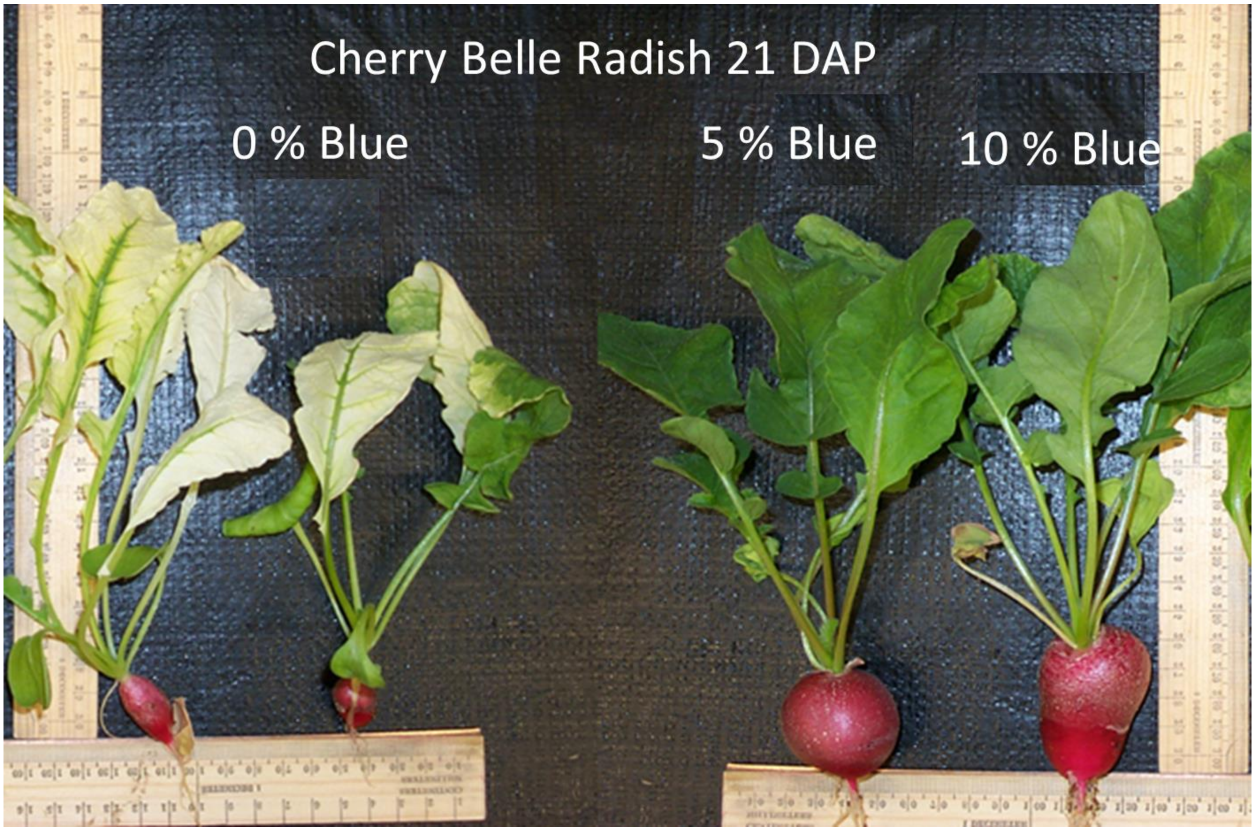

Figure 1: Blue light in the spectrum is critical for normal radish development. 'Cherry Belle' Radish grown under red/blue LEDs at 300 µmol m^{-2} s^{-1} PAR with 0, 5 or 10 µmol m^{-2} s^{-1} of blue light in the spectrum.(Stutte, unpublished)

Figure 2: Lettuce grown under red/blue LEDs only has a dark-purple-to-black appearance due to high absorbance of these wavelengths (Massa et al., 2008. HortScience 43:1951-1956).

Figure 3: Inclusion of green LEDs in a sole-source lighting spectrum results in a more 'normal' appearance of plants, facilitating visual assessment (Massa et al., 2008. HortScience 43:1951-1956).

Figure 4; LEDs provide a capability to customize the lighting spectrum to enhance the concentration of bioactive compounds in plant tissue.

Figure 5: Astronaut Steve Swanson preparing to harvest lettuce grown under LEDs in the VEGGIE Plant-growth chamber on the International Space Station (Image credit/NASA).

Figure 6: Dr. Raymond Wheeler (NASA, Kennedy Space Center) inspects red/blue LED array in the plant atrium of NASA's ground-based Habitat Demonstration Unit.